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WINDOW BREAKAGE INDUCED BY EXTERIOR FIRES

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Notice

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Abstract

Exterior fires can penetrate building envelopes via a number of pathways to become interior fires. One pathway is through windows and other glazed openings that have been broken by fire-induced stresses. A number of small- and large-scale experiments have been conducted to evaluate the performance of various window assemblies, glazing materials and potential protective treatments under the influence of imposed radiant heat fluxes ranging from 0.2 to 1.8 W/cm^2. Window assemblies include single- and double-pane windows with wood, vinyl and vinyl-clad wood frames. Glazing materials include ordinary single- and double-strength plate glass, tempered glass and a heat-resistant ceramic glass. Potential protective treatments include insect screens, vinyl film sun shades and aluminum foil. The application of aluminum foil over the exterior side of a window was found to be an effective treatment to prevent window breakage induced by an exterior fire. This simple treatment could be implemented by homeowners or other occupants of existing buildings in advance of an approaching exterior fire. Tempered glass and heat-resistant ceramic glass did not break under the influence of the imposed heat fluxes; mounted in a suitable fire resistant frame, they could be candidates for use in new windows where exposure to an exterior fire is expected. Vinyl-frame windows did not perform well under the exposure of imposed heat fluxes. The vinyl frames and sashes of these windows lost strength, distorted and sagged, permitting openings to develop. Consequently, vinyl-frame windows would not be suitable for use with fire resistant glazing materials.

Keywords: glass breakage; window fire tests; building envelope; wildland-urban interface

INTRODUCTION

Fire transmission from the exterior to the interior of a building is a significant aspect of wildland-urban interface fires, earthquake-induced fires and other conflagrations in developed areas. Exterior fires may penetrate a building envelope via a number of pathways. One pathway is through windows and other glazed openings. This mode of fire transmission is the subject of this report.

Failure mechanisms and potential remedial measures for windows exposed to uniform radiant heat fluxes have been addressed experimentally. This experimental program is described along with observations, findings and conclusions based on the experiments. A number of small- and real-scale experiments have been performed. Small-scale screening experiments with representative window assemblies and various treatments have been conducted to evaluate expected performance under simulated radiant exposure conditions and to identify the most promising treatments to prevent exterior fire-induced window breakage and fire transmission to the interior. Baseline real-scale tests using commercially available residential double-hung window assemblies have also been conducted to evaluate the performance of real-scale residential windows and to assess the applicability of the small-scale experiments. The treatments that seemed most likely to succeed based on the screening experiments were then subjected to real-scale exposures using commercially available residential window assemblies.

Previous research on window breakage under fire exposure is reviewed. Most of this previous work has addressed glass exposure to interior fires, not to exterior fires. The distinction is in the exposure conditions to which the window is subjected. In interior fires a layer of hot, buoyant gases forms beneath the ceiling and descends, subjecting the inside of the windows to a two-layer convective and radiative environment. In exterior fires, other than facade fires, the fire source is typically located some distance from the exposed window and consequently the exterior of the window is subjected to fairly uniform, purely radiative heating. This changes to combined convective and radiative heating when flames contact the window, as in floor-to-floor fire spread along a building facade. This research has focused on the case of purely radiative, fairly uniform exposure of the exterior side of window assemblies. Direct flame impingement on a window is not addressed here.

BACKGROUND

A number of investigators have studied glass breakage in compartment fires. Emmons (1986) pointed out that very little was known scientifically about this topic. He referred to a senior thesis paper prepared at Harvard by Barth and Sung (1977) as the first scientific study of this topic. Subsequent to Emmons's identification of this topic as one of many outstanding issues in fire science, experimental and theoretical studies of window breakage due to fire have been conducted by Keski-Rahkonen (1988, 1991), Pagni (1988) and Joshi (1991), Joshi and Pagni (1994, 1994a), Skelly, et al. (1991), and Silcock and Shields (1993).

These studies have all addressed the response of window glass to interior compartment fires. In this scenario, an enclosure fire produces a heat flux on a window assembly from the inside. The window assembly consists of a plate of glass supported in a frame such that the frame shields the border of the glass from the incident heat flux. The heat flux absorbed by the field of the glass causes the exposed glass to heat up, while the shielded glass border remains cool. The temperature difference between the glass field and the glass border induces tension stresses in the cool glass border as the field tries to expand but is constrained by the border. With sufficient heating, these thermally induced stresses exceed the yield stress of the glass and the glass cracks.

In this scenario of a window in a frame, the glass initially cracks at points of stress concentration along its edge. This is typically at locations where imperfections exist, such as at notches caused by cutting of the glass, or where the glass is already under some stress, such as at locations where glazing points hold the glass in place. Once the glass begins to fail, a bifurcating fracture pattern typically develops, with cracks propagating from the perimeter of the glass into the field. Cracks may merge in the field of the glass and may fully surround sections of the glass. This sometimes leads to some or all of the glass falling out of the window, causing a new vent to occur in the compartment boundary. In other cases, however, the glass fractures but remains in place. The conditions under which window glass will crack <u>and</u> fall out remain unresolved.

For interior fires, the new vent changes the ventilation characteristics of the compartment. It may provide a new path for fresh air to enter the compartment, which will increase the burning intensity of an underventilated fire, perhaps to flashover conditions. It may also provide a new path for flames and combustion products to leave the compartment and threaten other parts of the building. For these and other reasons, there is significant interest in window breakage during a compartment fire and in ways to prevent such breakage.

While glass breakage due to exterior fires has not been studied as extensively as glass breakage due to interior compartment fires, this subject warrants further consideration. A broken window represents one of the potential transmission paths for an exterior fire to penetrate a building envelope to become an interior fire. The new vent provides a path for burning brands and perhaps flames to enter a building and ignite light combustibles, such as bedding, upholstery or window coverings. Such transmission is critical in all conflagration scenarios, including wildland-urban interface and post-earthquake fires.

Glass breakage due to both interior and exterior fires may be significant in multi-floor building fires, such as occurred at the Las Vegas Hilton Hotel in 1981 and the First Interstate Bank in 1988. In these fires, windows on the floor of fire origin broke as a result of the interior fire, while windows on floors above the floor of fire origin most likely broke as a result of exposure to flames extending outside the buildings from floors below. Once broken, these upper story windows provided a pathway for fire to reenter the building and continue the vertical propagation of these fires. In the case of the Las Vegas Hilton Hotel, the fire spread vertically for 20 stories, probably via this mechanism.

Concern about bushfires and wildland-urban interface fires has resulted in at least two experimental evaluations of window performance under exterior fire conditions. As a result of the 'Ash Wednesday' fire in Australia on 16 February 1983, McArthur (1991) undertook an investigation of the performance of aluminum- and timber-framed windows subjected to a furnace exposure intended to represent an exterior fire. Cohen (1994) has begun to address experimentally window breakage from exterior fires in support of the Structural Ignition Assessment Model (SIAM) being developed by Cohen and coworkers at the USDA Forest Service (1991) to address wildland-urban interface fires.

Pagni (1988) suggests a simple strain criterion for the glass temperature increase, ΔT, required to break windows in fires:

$$\Delta T = g(\sigma_b / E\beta)$$

where g is a geometric factor of order one, σ_b is the tensile strength at breakage, E is Young's Modulus of Elasticity for the glass and β is the thermal coefficient of linear expansion. Pagni and Joshi (1991) report representative window glass (soda-lime) properties gleaned from the literature and calculate breaking strains and associated temperature increases at breakage based on these properties:

$\beta \times 10^6$ (K^{-1})	$\sigma_b \times 10\text{-}7$ (N/m^2)	$E \times 10^{-7}$ (N/m^2)	strain (%)	ΔT (K)
9.5	4.7	7.0	0.07	70
9.2	2.0-5.0	7.2	0.03-0.07	30-75
8.5	5.5-13.8	7.24	0.08-0.19	90-220
9.0	3.5-7.0	7	0.05-0.10	55-110

Pagni and Joshi note that the relatively large range of values is due to the uncertainty in the tensile stress at breakage, σ_b. Joshi and Pagni (1994a) observe that glass strength depends strongly on the treatment and handling of its surface, where tiny flaws lead to weakening and failure by brittle fracture. Larger surfaces are more likely to have more severe flaws, so the strength of glass generally decreases with increasing size.

Joshi and Pagni (1994a) performed experiments on 59 plate glass samples using a four-point flexure method to determine the breaking stress distribution and found the distribution to be described well by a three-parameter cumulative Weibull function. They conclude that a breaking stress of 40 MPa is a reasonable value to use in breaking calculations for ordinary glass. They also note that the breaking patterns of the test specimens suggest that fractures initiate at edge imperfections rather than at surface flaws.

EXPERIMENTAL PROGRAM

The experimental program undertaken to evaluate window breakage induced by exterior fires includes two elements:

- Small-scale screening experiments of representative glazing systems and potential protective treatments
- Large-scale experiments of baseline configurations and promising protective treatments using commercially available residential window assemblies

Small-scale screening experiments

Sixty-one small-scale screening experiments were conducted in the gas-fired radiant heat exposure apparatus shown schematically in Figure 1. These experiments were conducted to evaluate the performance of different exemplar glazing systems and potential protective treatments under imposed radiant heat fluxes ranging from approximately 0.2 to 1.6 W/cm^2. At the low end of this range, windows did not break under the imposed heat flux, while at the high end, the wood frames used for the window assemblies charred and smoked, and in some cases smoldered, indicating the onset of ignition. Higher heat fluxes could not be achieved in this gas-fired radiant heat exposure apparatus.

The glazing materials evaluated include single-strength and double-strength ordinary plate glass, tempered glass and a heat-resistant ceramic glass. Potential protective treatments evaluated include insect screening, vinyl film sun shade and aluminum foil. These treatments were applied to the exposed side of the window assembly, except for one test in which aluminum foil was attached to the inside (unexposed) side of the window. Table 1 summarizes the different configurations used for the small-scale experiments, along with the results of the small-scale experiments.

The gas-fired radiant heat exposure apparatus used for the small-scale experiments includes two vertical banks of gas-fired burners located opposite the test window assembly. Each bank consists of five porous ceramic panels and measures 38 cm wide by 83 cm high. The panels are each oriented at an angle of 30 degrees with respect to the window assembly to produce a fairly uniform radiant heat flux at the window assembly. The side panels were covered with aluminum foil to reflect heat back into the test chamber and thus maximize exposure to the test assembly. Test window assemblies are oriented at the center height of the gas panels. The outside walls of the test chamber consist of water-cooled copper plates to minimize heating of the laboratory space. Combustion products are vented through a hood and duct system located above the test rig. Figure 2 is a photograph of the test apparatus, taken from the burner panel side.

Representative window assemblies were fabricated and subjected to constant and fairly uniform radiant heat fluxes ranging from approximately 0.2 to 1.6 W/cm^2 in this apparatus. Window frames with outside dimensions of 28 cm wide by 39 cm high were fabricated of 38 mm by 38 mm Douglas fir lumber. The frames were squarely notched to a depth of 16 mm around the inside perimeter to hold the window glass panes, which had outside dimensions of 23 cm wide by 34 cm high. This provided an exposed field of 20 cm wide by 31 cm high and a shielded perimeter 13 mm wide around the edge of the glass. Glazing putty and glazing points were used to secure the glass to the frames; the putty provided the shielding. The window assemblies are illustrated schematically in Figure 3.

The window frames were mounted in a steel test frame, which slid on rails on the test rig. A steel shutter that dropped down over the window location on the test rig shielded the test specimens from the heat flux until the start of a test. Before each experiment, heat fluxes were measured at the center exposed surface of the window assembly using a special window frame with a Gardon-type total heat flux meter mounted at its center. Once the desired heat flux was achieved and had stabilized, the flux measurement assembly was removed from the test rig, the shutter was closed and a test specimen was mounted. The heat flux meter was then positioned 2.5 cm behind the center of the glass in order to measure the heat flux being transmitted through the glass.

With the test frame in place on the rails, the shutter was opened, the test frame was rapidly slid into its test position and a stopwatch was started to measure the time to glass breakage. At the same time, the heat flux transmitted through the glass was recorded with a data acquisition system.

Large-scale experiments

Nineteen experiments were conducted with commercially available residential window assemblies. In these experiments, double hung windows, nominally 61 cm wide by 81 cm high, were mounted in the center of a 1.2 m wide by 2.4 m tall wall. The wall and window assemblies were constructed to be reasonably representative of typical wood frame residential construction in the United States. The wall frame was constructed with nominal 2x4 lumber. During preliminary calibration experiments, the exterior (exposed) side of the wall was sheathed with 12.7 mm thick gypsum wallboard, but the paper facer degraded under the imposed heat flux, so the gypsum wallboard was replaced with 12.7 mm thick calcium silicate board for subsequent tests. The interior side of the wall assembly was not sheathed.

A number of different commercial window assemblies were evaluated. These included single- and double-pane windows with frames of wood, vinyl and vinyl-covered wood. For two of the experiments, the exterior (exposed) side of the windows were covered with aluminum foil. The large-scale experiments are summarized in Table 2.

The windows were subjected to fairly uniform radiant heat fluxes using a large-scale electrical resistance radiant panel developed by Ohlemiller. This panel consists of two separate panels nominally 38 cm wide by 198 cm tall. The two panels are oriented such that each points inward at an angle of approximately 15°; the panels are separated by a space approximately 16 cm wide. The radiant panel was positioned to be centered along the vertical centerline of the test wall, with the edges of the panels located 30 cm away from the surface of the test wall. The bottom of the radiant panel is located 30 cm above the floor. The arrangement of the wall assembly and the large-scale radiant panel is shown schematically in Figure 4.

The wall panels were instrumented with four thermocouples and two heat flux meters. For window assemblies with single glazing, two thermocouples were attached to the glass on the exposed side of the upper and the lower panes of the double hung windows, while the other two thermocouples were embedded in the adjacent window frames. The frames were drilled to the depth of the glazing on the unexposed side of the assembly and the thermocouples were inserted in the drilled holes. For window assemblies with double glazing, the four thermocouples were attached to each of the panes of glass, the exposed and unexposed lights of both the top and bottom windows.

One of the heat flux meters was used to measure the heat flux being transmitted through the lower window of the double hung window assembly. This meter was placed 5 cm behind the glass at the center of the lower window. The other heat flux meter was used to measure the heat flux at the lower edge of the window assembly along the vertical centerline. For wood-frame windows, this meter was mounted in a hole drilled in the bottom sash of the lower window. For vinyl-frame windows, this meter was mounted in the wall assembly, directly below the window assembly.

Measured temperature and heat flux data for the large-scale experiments are shown in Figures 5 to 20. These figures also show calculated glass temperatures, based on the models described in Appendix A. These calculations were computed with two spreadsheet programs, one for the single-pane windows and one for the double-pane windows, using the Euler numerical method.

OBSERVATIONS

A number of observations have been made with respect to the small-scale and large-scale experiments that have been conducted. For the small-scale experiments, these observations include:

- The critical imposed heat flux needed to cause the single-strength glass windows without protective treatments to fail is somewhere in the range of 0.4 to 0.5 W/cm^2. At lower heat fluxes of approximately 0.33 W/cm^2, these window assemblies did not fail, while at higher heat fluxes, they always failed. Within this critical range, some window assemblies failed, while others did not.

- For single-strength glass windows without protective treatments, the heat load at failure, defined as the product of the imposed heat flux by the breakage time, had an average value of approximately 96 J/cm^2 for cases where glass breakage occurred, and a range of 27 to 161 J/cm^2 for these cases, as shown in Figure 21. While there appears to be a slight trend towards lower heat loads at higher heat fluxes, the scatter in the data make this observation inconclusive.

- For single-strength glass windows without protective treatments, the heat flux transmitted through the glass reached approximately one-third of the radiant flux imposed on the glass as steady-state conditions were approached.

- When windows did break in these experiments, the glass remained in place for the most part. Breakage typically occurred with cracks initiating along one or more edges of a window. These cracks would bifurcate in the field of the window. In some cases, cracks with different origins would merge, creating sections of glass completely surrounded by cracks, but these sections typically remained in place nonetheless.

- Breakage did not occur when aluminum foil was applied to the exterior, exposed side of the window. For these cases, the aluminum foil reflected the incident heat back into the test chamber, keeping the window relatively cool. Less than 2 % of the imposed heat flux was transmitted through windows for these cases.

- Breakage did occur when aluminum foil was attached to the interior, unexposed side of a window. This breakage occurred when the imposed heat load at breakage was approximately 70 J/cm^2, a value approximately 70% of the average value for exposed glass. This result is consistent with the reflection of transmitted heat back into the glass from the unexposed side, which would cause the window to heat up faster and break more quickly. In this case, the transmitted heat flux was less than 2% of the imposed heat flux. Although the window cracked relatively quickly, the glass and aluminum foil remained in place.

- Window breakage also occurred when aluminum foil with a 127 mm square hole at the center was attached to the exposed side of the window frame. In these cases, however, the breakage pattern was different from the other cases, suggesting a different failure mechanism. For these cases, the breakage initiated at the center of the window, directly behind the hole in the aluminum foil, with a fracture pattern resembling fish scales. A few cracks propagated from this central region to the edges of the window. Compared with tests without any protective treatment conducted at the same heat fluxes with the same glass on the same days, the imposed heat load at glass failure was two to three times higher for the windows with the aluminum foil.

- Bright aluminum and black fiberglass insect screens attached to the exposed side of the window frame did not prevent glass breakage for single strength windows, but they did increase the average imposed heat load at breakage to approximately 116 J/cm^2, an increase of 21% compared with exposed single strength windows. Both types of insect screen remained in place during exposure.

- Vinyl sun shade film adhered to the unexposed (inside) side of a window did not prevent glass breakage. If anything, the data suggest that this treatment may expedite breakage.

- Neither heat resistant ceramic glass or tempered glass failed when exposed to heat fluxes of approximately 1.6 W/cm^2 for periods of up to 15 minutes. In these experiments, the wood frame and glazing putty began smoking. The wood frames charred under this exposure and the glazing putty puffed up and developed voids.

For the large-scale experiments with commercially available double-hung residential window assemblies, the following observations are made:

- The single-pane wood-frame windows always failed at heat fluxes above 1.0 W/cm^2 and did not fail at heat fluxes of less than 0.70 W/cm^2. For those cases where failure occurred, the average measured glass temperature at failure was 157°C for the upper light and 123°C for the lower light. The measured frame temperatures at first failure were 61°C for the upper light and 55°C for the lower light. Thus, the average temperature differences between the glass and the frame at failure were 96°C for the upper light and 68°C for the lower light, respectively. The average imposed heat load at failure was 97 J/cm^2 for the upper light and 77 J/cm^2 for the lower light, with a range of 44 to 167 J/cm^2 for the upper light and 42 to 123 J/cm^2 for the lower light, respectively.

- The exposed (outside) lights of double-pane wood-frame and wood-frame with vinyl trim windows failed in all tests of these windows, in which imposed heat fluxes ranged from 1.05 to 1.8 W/cm^2. The average measured temperature at failure was 149°C for the upper light and 143°C for the lower light, with a range of 134 to 162°C for the upper light and 119 to 174°C for the lower light, respectively.

- The unexposed (inside) lights of double-pane wood-frame windows failed in all tests of these windows, in which imposed heat fluxes ranged from 1.05 to 1.8 W/cm^2.

- The unexposed (inside) lights of double-pane wood-frame with vinyl trim windows did not fail in any tests of these windows, in which imposed heat fluxes ranged from 1.10 to 1.45 W/cm^2.

- Double-pane vinyl-frame windows failed catastrophically, with the development of large through penetrations caused by sagging and collapse of the window frames, in all tests of these windows. Heat fluxes for these tests ranged from 0.8 to 1.6 W/cm^2.

- For the double-pane vinyl-frame windows, the imposed heat load at breakage of the exposed panes averaged 22 J/cm^2 for the upper light and 61 J/cm^2 for the lower light, with ranges of 16 to 25 J/cm^2 for the upper light and 47 to 68 J/cm^2 for the lower light. The measured temperature at breakage of the exposed panes averaged 97°C for the upper light and 145°C for the lower light, with a range of 93 to 100°C for the upper light and 130 to 161°C for the lower light, respectively.

- The unexposed lights of the double-pane vinyl-frame windows did not always fracture, but through penetrations always formed. In some cases, the unexposed lights slipped out of the vinyl sashes as the sashes and frames distorted, sagged and lost strength due to the imposed heat flux. The upper window frames sagged considerably under all imposed heat fluxes, ranging from 0.8 to 1.6 W/cm^2. This sagging permitted through openings to form between the top rail of the window sash and the window frame and between the window glazing and the top rail of the sash. Sagging and distortion of the upper windows would have been worse had the lock between the upper and lower windows not been engaged.

FINDINGS AND CONCLUSIONS

Based on the small- and large-scale experiments conducted with a range of window assemblies, glazing materials and protective treatments, a number of findings can be discussed and conclusions drawn. These include:

- Ordinary window glass can break under imposed heat flux conditions of approximately 0.4 to 0.5 W/cm^2 and higher. For exposed glass supported around its edge in a shielded frame, fracture initiates at the edges, most likely at locations where imperfections or other points of stress concentration exist.

- The breakage of ordinary glass in window frames is generally consistent with the theory propounded by Emmons and developed in detail by Pagni and Joshi, with the exception that heating of the window glass shielded by the frame seems to be more significant than thought by Pagni and Joshi. The effect of this is to increase the temperature at breakage of the exposed glass, such that the temperature difference at breakage between the exposed field and the shielded edge are consistent with the values suggested by Pagni and Joshi.

- An effort was made to compare results of calculations of the BREAK1 computer program developed by Pagni and Joshi with experimental results. The BREAK1 program did not seem to handle the specified radiation only boundary conditions properly, however, and calculated insignificant temperature increases in the glass. Spreadsheet templates were developed to perform calculations instead.

- The spreadsheet templates use a simple Euler numerical method to calculate glass temperature as a function of time in response to a specified constant imposed heat flux at one surface with convection and reradiation from both surfaces. Two templates, called GLASSTMP.XLS and GLASTMP2.XLS, have been developed to address single- and double-pane windows, respectively. These templates are described in Appendix A. Results of calculations using these templates are shown on Figures 5 through 20, along with the measured temperatures for the large-scale window tests.

- Insect screens seem to prolong the time to breakage compared to exposed windows, but fracture still occurs. This increased time to breakage is consistent with a net reduction of heat flux to the window associated with the shading factor of approximately 25% provided by the insect screen. While insect screens may not prevent window breakage, they can prevent the passage of burning brands through a window opening and thus may have some benefit where flying brands are the mode of fire transport (BORAL, undated).

- Vinyl film sun screens provide no additional protection over exposed ordinary window glass. If anything, when such materials are attached to the inside (unexposed) side of a window, they seem to decrease the time to breakage. This behavior is consistent with the film reflecting some of the transmitted heat back into the window.

- Aluminum foil applied to the exterior (exposed) side of window assemblies proved to be a very effective treatment for preventing window breakage induced by a radiant heat flux. This treatment was equally effective whether the aluminum foil was stapled to the window frame or glued directly to the window glazing. The durability of different methods of attachment under high wind conditions has not been investigated, but gluing the aluminum foil directly to the window glazing would appear to be the more durable method of the two investigated. This treatment appears to be suitable for existing windows with ordinary glass, where the use of more heat resistant glazing materials is precluded.

- Aluminum foil applied to the interior (unexposed) side of window assemblies proved to be ineffective as a means of preventing window breakage. If anything, when aluminum foil is attached to the inside (unexposed) side of a window, it seems to decrease the time to breakage. This behavior is consistent with the foil reflecting the transmitted heat back into the window, causing it to heat up more quickly.

- Aluminum foil applied to the exterior (exposed) side of a window assembly, but with a hole in the foil as might occur accidentally during installation or as a result of high winds, provides some additional protection in comparison with an exposed window, but does not prevent a window from breaking. The fracture pattern associated with this scenario is different from the others, suggesting a different failure mechanism. In this scenario, fracture initiates in the field of the glass, probably from compressive forces rather than tensile forces, causing a "fish scale" pattern of breakage in the glass exposed through the hole in the foil.

- Tempered glass and heat-resistant ceramic glass both remained intact throughout the period of all small-scale tests of these products, at heat fluxes ranging up to approximately 1.6 W/cm^2. At this heat flux, the wood frame and glazing putty smoked and charred, suggesting that failure of window assemblies containing these glazing materials might eventually occur as a result of failure of the frame or glazing system rather than fracture of the glazing material. Based on the small-scale screening tests with these two glazing materials, they can both be recommended for further consideration as potential glazing materials for new windows in areas subject to exterior fires, provided they are used with suitable frames and glazing systems.

- Vinyl-frame windows faired poorly in the large-scale experiments, at imposed heat fluxes ranging from 0.8 to 1.6 W/cm^2. The vinyl frames and sashes lost strength, sagged and distorted under the imposed heat fluxes, typically within a matter of minutes. This distortion led to the development of through penetrations in the windows, even if the glazing remained intact. Such penetrations would permit the entry of fire brands into a building. For these reasons, vinyl-frame windows do not seem to be appropriate for use in buildings requiring fire resistant glazing.

SUMMARY

Failure mechanisms of windows subjected to radiant heating from exterior fires have been addressed experimentally. The performance of such windows has proven to be generally consistent with the theory of glass breakage described by previous investigators. The question of when a broken window will fall out after it breaks remains unanswered. In the experiments conducted for this program, windows tended to remain in place after fracturing, but field experience suggests that broken windows frequently fall out. Further work is needed to investigate this question as well as questions regarding the effects of direct flame impingement on window assemblies.

A number of potential remedial strategies have been considered to prevent or delay glass breakage. For existing window installations, the application of aluminum foil to the outside of the window surface appears to be highly effective. This is a simple remedy that could be implemented by homeowners and other building occupants on relatively short notice. For new installations, the use of tempered glass or ceramic glass appears to offer a high level of protection, without the need for active intervention in the path of an advancing conflagration. Such glazing materials need to be installed in fire resistant window assemblies that will not fail during the expected period of exposure. Vinyl-frame windows are inappropriate for such applications because the vinyl sashes and frames distort and lose strength under the influence of moderate imposed heat fluxes.

Either of these solutions would increase the fire endurance of ordinary windows considerably, to the point where fire transmission through windows becomes much less likely. Without similar upgrades in the fire endurance of other vulnerable fire transmission paths, however, efforts to increase the fire endurance of windows may largely be in vain.

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Appendix A

One-dimensional lumped capacity model for glass heating under imposed radiant heat flux

Case 1: Single-pane windows

This model treats the glass plate as a thermally thin solid, with density ρ, specific heat c and thickness L, that heats up uniformly under the influence of an imposed radiant heat flux at one of the glass surfaces. The glass loses heat from both surfaces due to convection and reradiation. It is assumed that the glass absorbs some specified fraction α of the incident radiant heat flux $\dot{q}_r$. Convection and reradiation occur from both surfaces. Convection is specified in terms of average convective coefficients, h_1 and h_2, for each of the surfaces. The environmental temperature on both sides of the glass is assumed to be T_o. Reradiation from the two surfaces is assumed to occur at a specified effective emissivity of ε. With these assumptions and specifications a heat balance on the glass can be written as:

$$\rho c L \frac{dT_g}{dt} = \alpha \dot{q}_r - \left[(h_1 + h_2)(T_g - T_o) + 2\varepsilon\sigma(T_g^4 - T_o^4)\right]$$

This equation is rearranged to solve for the rate of temperature rise:

$$\frac{dT_g}{dt} = \frac{\alpha \dot{q}_r - \left[(h_1 + h_2)(T_g - T_o) + 2\varepsilon\sigma(T_g^4 - T_o^4)\right]}{\rho c L}$$

The Euler method is used to numerically calculate the temperature history of the glass:

$$T_g' = T_g + \frac{dT_g}{dt}\Delta t$$

where the prime denotes the glass temperature at time $t+\Delta t$.

This heat balance and solution technique have been programmed into a spreadsheet template called GLASSTMP.XLS. This template has been used to compare calculated glass temperatures with measured temperatures for the single-pane large-scale window experiments. These comparisons are shown on Figures 5, 6, 9, 10, 11, 12 and 17, for experiment numbers 1, 2, 5, 6, 7, 8 and 13, respectively. Properties used for these comparisons include:

$\rho = 2700$ kg/m^3; c = 0.84 kJ/kg.K; L = 0.0024 m
$\alpha = 0.8$; $\varepsilon = 0.9$; $h_1 = 0.005$ kW/m^2.K; $h_2 = 0.010$ kW/m^2.K

Case 2: Double-pane windows

This model treats the glass plates as thermally thin solids, each of density ρ, specific heat c and thickness L, that heat up uniformly under the influence of an imposed radiant heat flux at the exposed surface of one of the glass panes. The exposed pane absorbs a specified fraction α of the incident radiant heat flux $\dot{q}_r$, while the remaining fraction (1 - α) is transmitted through the exposed pane. The exposed pane loses heat from its exposed surface due to convection and reradiation; it loses heat from its rear surface due to reradiation exchange with the unexposed pane through the air gap between the panes. The factor ε_{12} accounts for the effective emissivities and the view factor between the panes. Convection and conduction within the air gap are neglected. The heat balance on the exposed pane, designated with subscript 1, is expressed as:

$$\rho c L \frac{dT_1}{dt} = \alpha \dot{q}_r - \left(h_1(T_1 - T_o) + \varepsilon_1 \sigma (T_1^4 - T_o^4) + \varepsilon_{12} \sigma (T_1^4 - T_2^4)\right)$$

The unexposed pane is heated by the fraction of the imposed heat flux that is transmitted through the exposed pane and by reradiation exchange with the rear face of the exposed pane. Of the fraction of the imposed heat flux that is transmitted through the exposed pane, (1 - α) $\dot{q}_r$, a specified fraction α is absorbed by the unexposed pane, with the remaining fraction transmitted through the unexposed pane. The unexposed pane loses heat from its rear surface due to convection and reradiation with the ambient environment. The heat balance on the unexposed pane, designated with subscript 2, can be expressed as:

$$\rho c L \frac{dT_2}{dt} = \alpha (1-\alpha) \dot{q}_r + \varepsilon_{12} \sigma (T_1^4 - T_2^4) - \left(h_2(T_2 - T_o) + \varepsilon_2 \sigma (T_2^4 - T_o^4)\right)$$

These equations are rearranged, by dividing both sides by the product ρcL, to solve for the rate of temperature rise for the two panes of glass. The Euler method is used to numerically calculate the temperature histories of the two panes:

$$T_g' = T_g + \frac{dT_g}{dt} \Delta t$$

where the prime denotes the glass temperature at time t+Δt, and the subscript g stands for glass panes 1 or 2, respectively.

These heat balances and solution technique have been programmed into a spreadsheet template called GLASTMP2.XLS. This template has been used to compare calculated glass temperatures with measured temperatures for the double-pane large-scale window experiments. These comparisons are shown on Figures 7, 8, 13, 14, 15, 18, 19 and 20, for experiment numbers 3, 4, 9, 10, 11, 14, 18 and 19, respectively. Properties used for these comparisons include:

$\rho = 2700$ kg/m^3; c = 0.84 kJ/kg.K; L = 0.0024 m
$\alpha = 0.8$; $\varepsilon_1 = \varepsilon_2 = 0.9$; $\varepsilon_{12} = 0.8$; $h_1 = 0.005$ kW/m^2.K; $h_2 = 0.015$ kW/m^2.K

Table 1. Summary of small-scale experiments

Test	Heat flux (W/cm2)		Break time	Heat load	Glass type	Protective treatment
	Imposed	Transmitted	(s)	(J/cm2)		
G1	1.40	0.54	79	111	DS	None
G2	0.90	0.29	195	176	DS	None
G3	0.95	0.31	129	123	SS	None
G4	0.95	0.31	92	87	SS	None
G5	0.95	0.33	106	101	SS	None
G6	1.00	0.38	115	115	SS	None
G7	1.00	No data	108	108	SS	None
G8	0.50	0.14	> 699	> 300	SS	None
G9	0.73	0.23	153	112	SS	None
G10	0.75	0.24	105	79	SS	None
G11	0.73	0.22	112	82	SS	None
G12	0.72	0.23	204	147	SS	None
G13	1.25	0.43	37	46	SS	None
G14	1.27	0.46	70	89	SS	None
G15	1.25	0.49	92	115	SS	None
G16	1.25	0.49	46	58	SS	None
G17	1.28	0.42	92	118	SS	Brite Al insect screen
G18	1.26	0.42	100	126	SS	Brite Al insect screen
G19	1.25	0.39	94	118	SS	Brite Al insect screen
G20	1.28	0.40	95	122	SS	None
G21	0.56	0.21	245	137	SS	None
G22	0.56	0.21	111	62	SS	None
G23	0.39	No data	380	148	SS	None
G24	0.50	0.18	321	161	SS	None
G25	0.50	0.15	72	36	SS	None
G26	1.18	0.44	71	84	SS	None
G27	1.18	0.01	> 900	> 1062	SS	Al foil
G28	1.15	0.39	117	135	SS	None
G29	1.02	No data	108	110	SS	Brite Al insect screen
G30	1.02	0.37	110	112	SS	Brite Al insect screen
G31	1.17	0.48	76	89	SS	None
G32	1.17	0.47	46	54	SS	None
G33	1.15	0.37	23	26	SS	None
G34	1.17	0.36	82	96	SS	None
G35	1.02	0.31	126	129	SS	Brite Al insect screen
G36	1.02	0.28	76	78	SS	Brite Al insect screen
G37	1.05	0.29	118	124	SS	Black FG insect screen
G38	1.02	0.25	130	133	SS	Black FG insect screen
G39	1.18	0.21	35	41	SS	Vinyl "Sun Shade"
G40	1.18	0.31	81	96	SS	Vinyl "Sun Shade"
G41	1.17	0.44	317	371	SS	Al foil w/5"x5" cutout
G42	1.52	0.45	40	61	SS	None
G43	1.53	0.48	89	136	SS	Al foil w/5"x5" cutout
G44	1.52	0.04	> 900	> 1368	SS	Al foil glued to glass
G45	1.52	0.04	> 900	> 1368	SS	Al foil glued to glass
G46	1.52	0.03	46	70	SS	Al foil glued to glass back
G47	1.52	0.53	110	167	SS	Al foil w/5"x5" cutout
G48	1.52	0.45	52	79	SS	None
G49	0.20	No data	> 1020	> 204	Ceramic	None
G50	0.33	0.12	> 1200	> 396	SS	None
G51	0.34	0.12	> 1200	> 408	SS	None
G52	0.48	0.18	297	141	SS	None
G53	0.48	0.16	208	100	SS	None
G54	0.48	0.19	> 1200	> 576	SS	None
G55	0.50	0.19	> 900	> 450	SS	None
G56	1.57	0.67	> 600	> 942	Ceramic	None
G57	1.56	0.71	> 900	> 1404	Ceramic	None
T1	1.05	0.40	>1200	> 1260	Tempered	None
T2	1.05	0.40	> 900	> 945	Tempered	None
T3	1.61	0.72	> 900	> 1449	Tempered	None
T4	1.60	0.72	> 900	> 1440	Tempered	None

Table 2. Summary of large-scale experiments

Test No.	Fig. No.	Window description			Panel setting (deg-C)	Approx. heat flux (W/cm2)	Initial glass breakage time (s)				Measured temperature at breakage time (C)				Ambient temp. (deg-C)
		Panes (1 or 2)	Frame	Covering			Upper light		Lower light		Upper light		Lower light		
							Outside	Inside	Outside	Inside	Outside	Inside/frame	Outside	Inside/frame	
1	5	1	Wood	None	540	1.10	95	#N/A	37	#N/A	151	65	83	40	26
2	6	1	Wood	None	620	1.80	90	#N/A	36	#N/A	202	90	110	48	27
3	7	2	Wood	None	620	1.80	32	165	32	116	157	131	119	87	27
4	8	2	Wood	None	540	1.10	56	375	78	280	138	50	152	52	27
5	9	1	Wood	None	400	0.40	NB	#N/A	NB	#N/A	128	85	134	113	24
6	10	1	Wood	None	470	0.70	NB	#N/A	NB	#N/A	181	90	172	134	27
7	11	1	Wood	None	540	0.90	NB	#N/A	NB	#N/A	228	115	210	116	30
8	12	1	Wood	None	620	1.20	40	#N/A	38	#N/A	119	30	117	34	28
9	13	2	Wood	None	620	1.20	45	295	90	255	142	149	174	118	31
10	14	2	Wood	None	670	1.45	36	201	40	218	162	140	127	131	32
11	15	2	Wood	None	670	1.45	55	224	46	130	158	137	133	87	30
12	16	1	Wood	Al foil	670	1.45	NB	#N/A	NB	#N/A	45	45	51	46	28
13	17	1	Wood	None	670	1.45	55	#N/A	85	#N/A	150	63	180	96	33
14	18	2	Wood/vinyl	None	620	1.20	50	NB	63	NB	134	267	155	250	33
15	-	2	Wood/vinyl	Al foil	670	1.45	NB	NB	NB	NB	Corrupt data file				
16	-	2	Wood/vinyl	None	670	1.45	35	NB	37	NB	Corrupt data file				
17	-	2	Vinyl	None	620	1.20	21	240	39	250	Corrupt data file				15
18	19	2	Vinyl	None	670	1.60	10	288	42	NB	100	172	161	262	19
19	20	2	Vinyl	None	540	0.90	31	NB	85	NB	93	265	130	246	19

Notes: NB – Glass did not break (fracture)
N/A – Not applicable (No interior light for single pane cases)

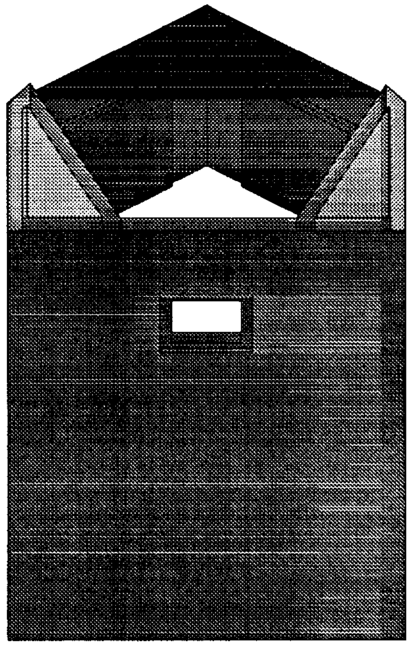

Figure 1. Schematic diagram of small-scale gas-fired radiant exposure apparatus.

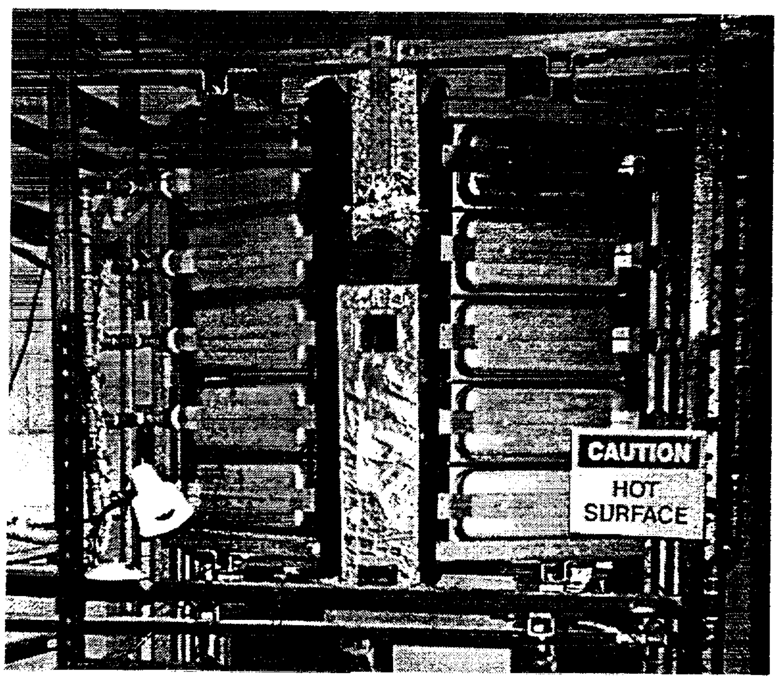

Figure 2. Photograph of small-scale gas-fired radiant exposure apparatus.

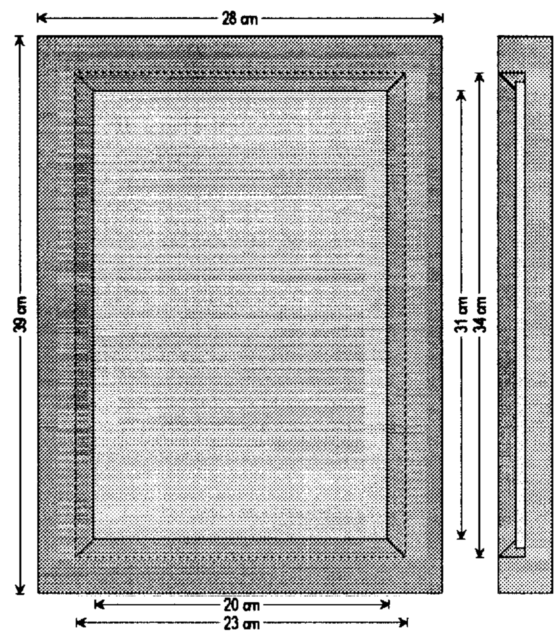

Figure 3. Diagram of small-scale window assemblies.

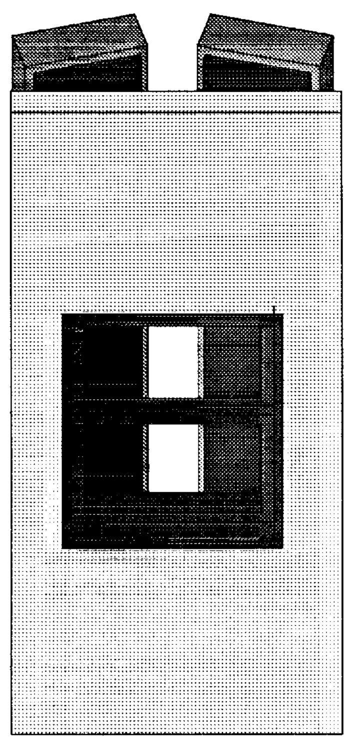

Figure 4. Perspective view of large-scale electric radiant panel apparatus.

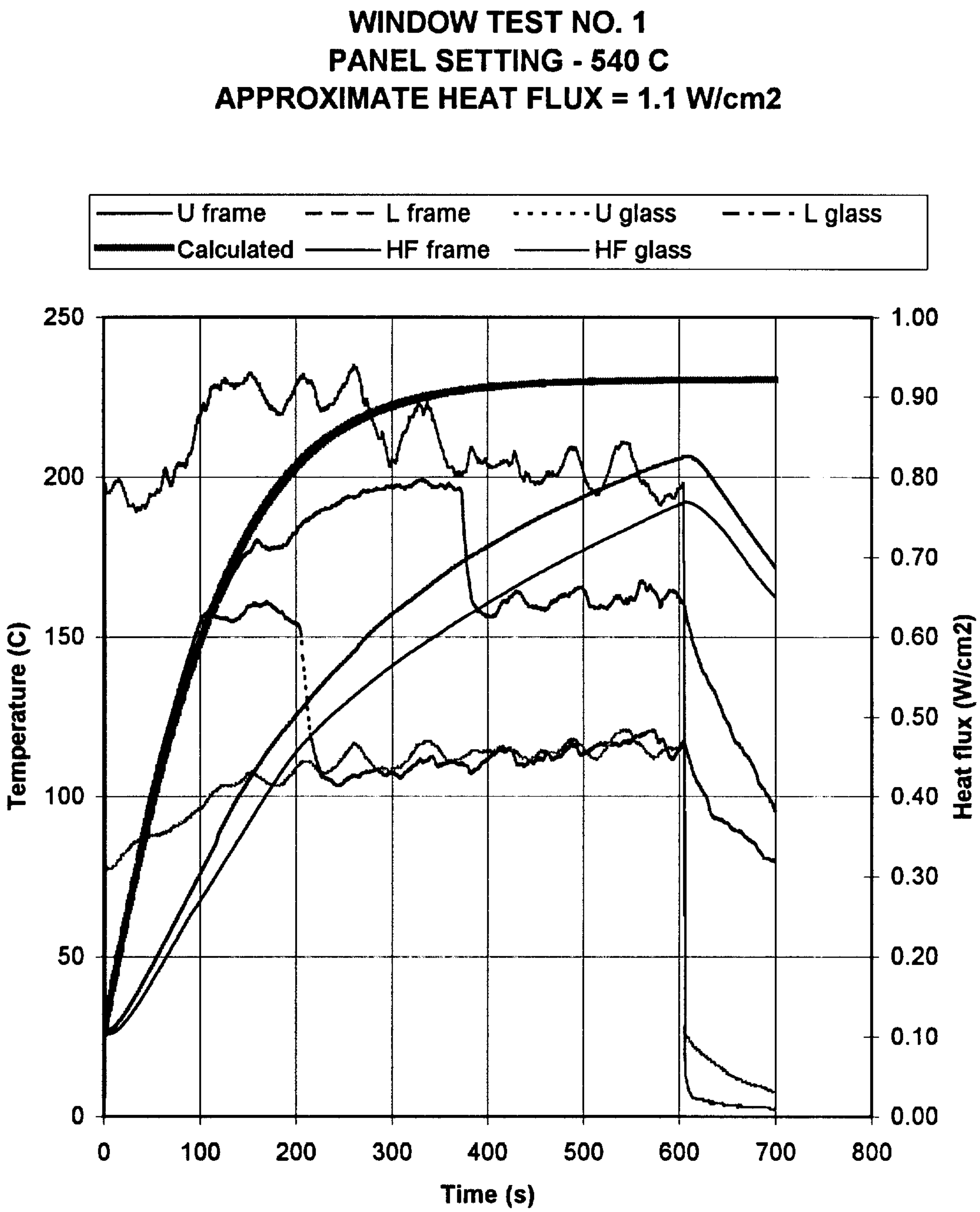

Figure 5. Temperature and heat flux data for large-scale Window Test 1.

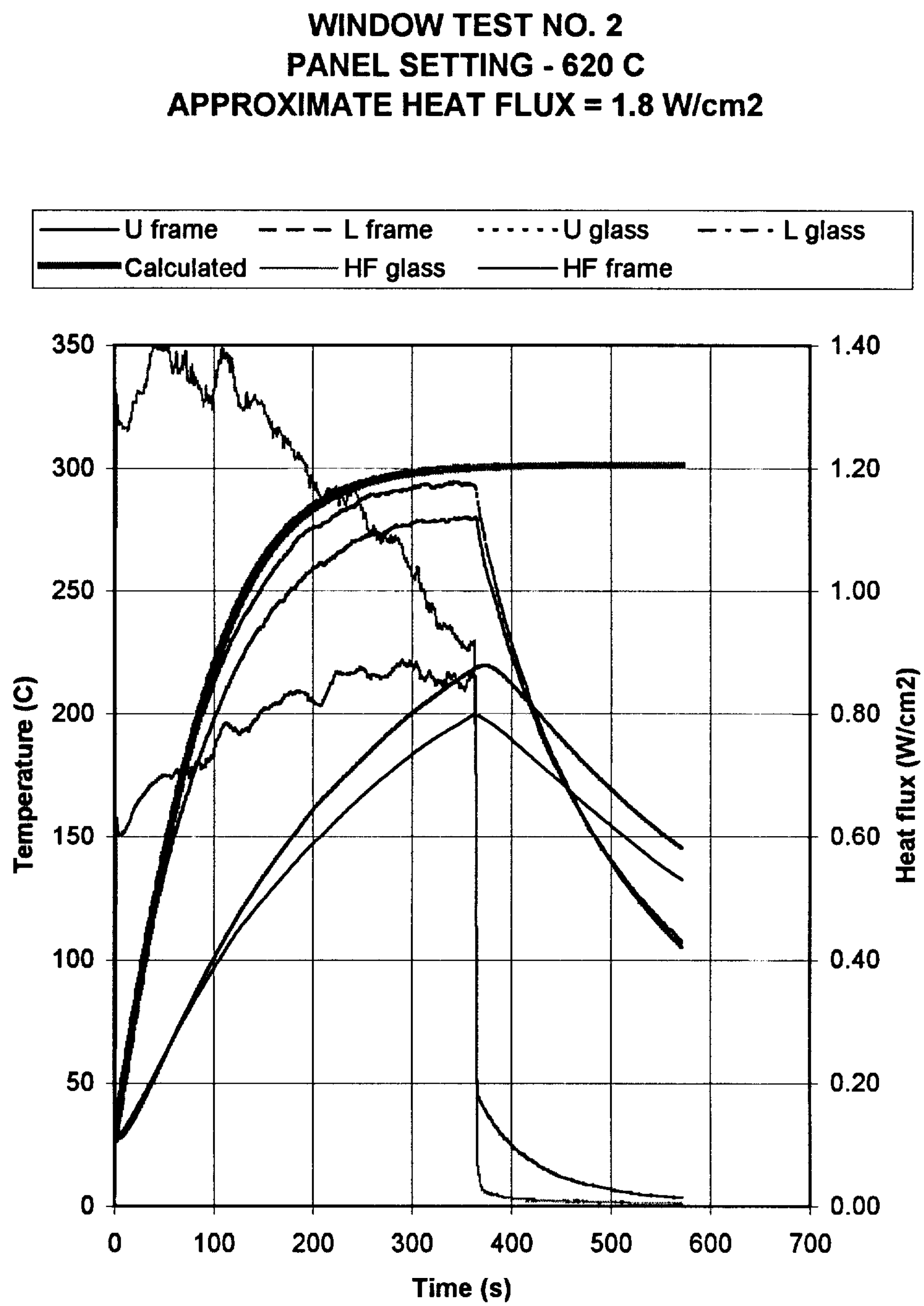

Figure 6. Temperature and heat flux data for large-scale Window Test 2.

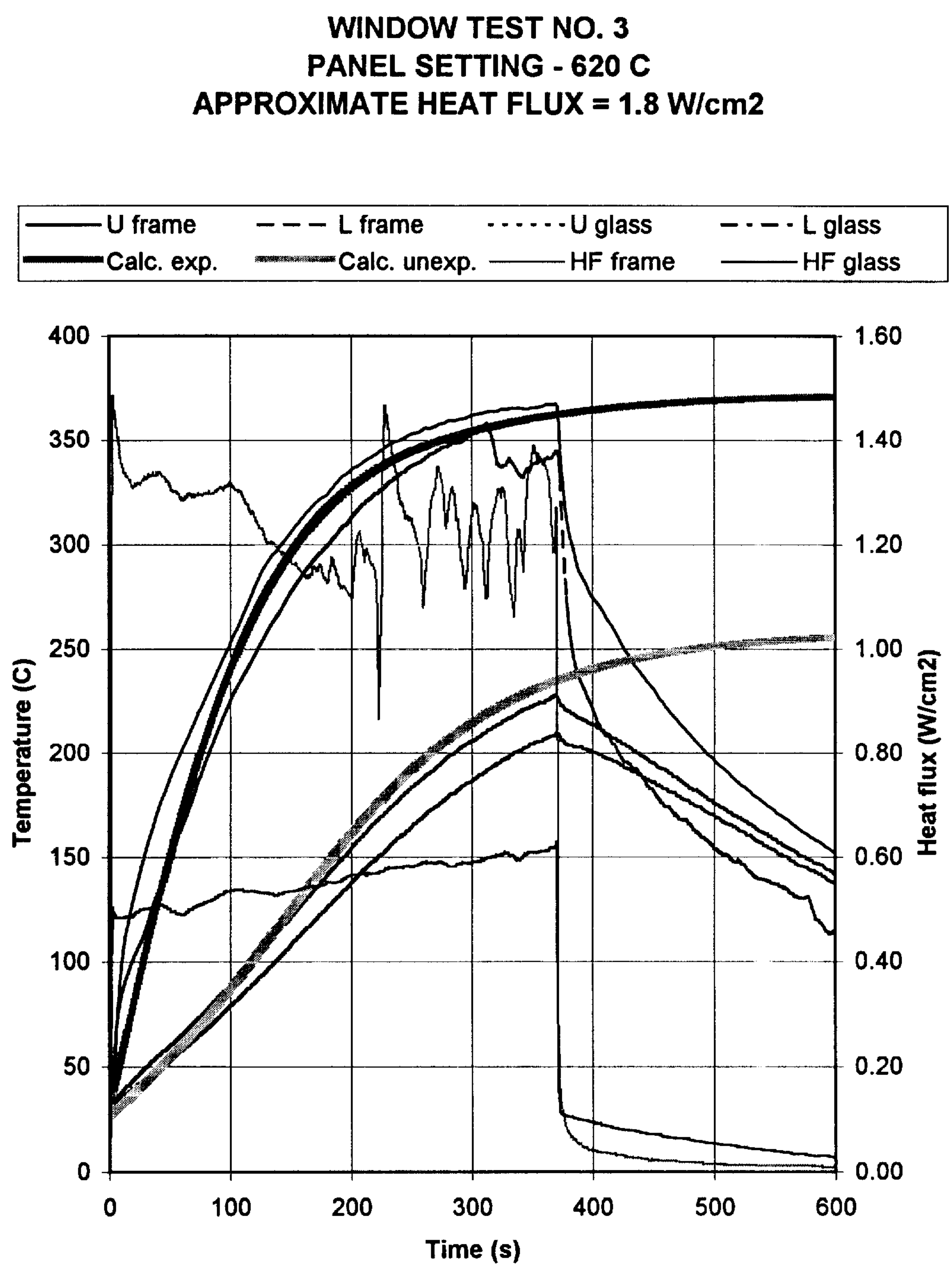

Figure 7. Temperature and heat flux data for large-scale Window Test 3.

WINDOW TEST NO. 4
PANEL SETTING - 540 C
APPROXIMATE HEAT FLUX = 1.1 W/cm2

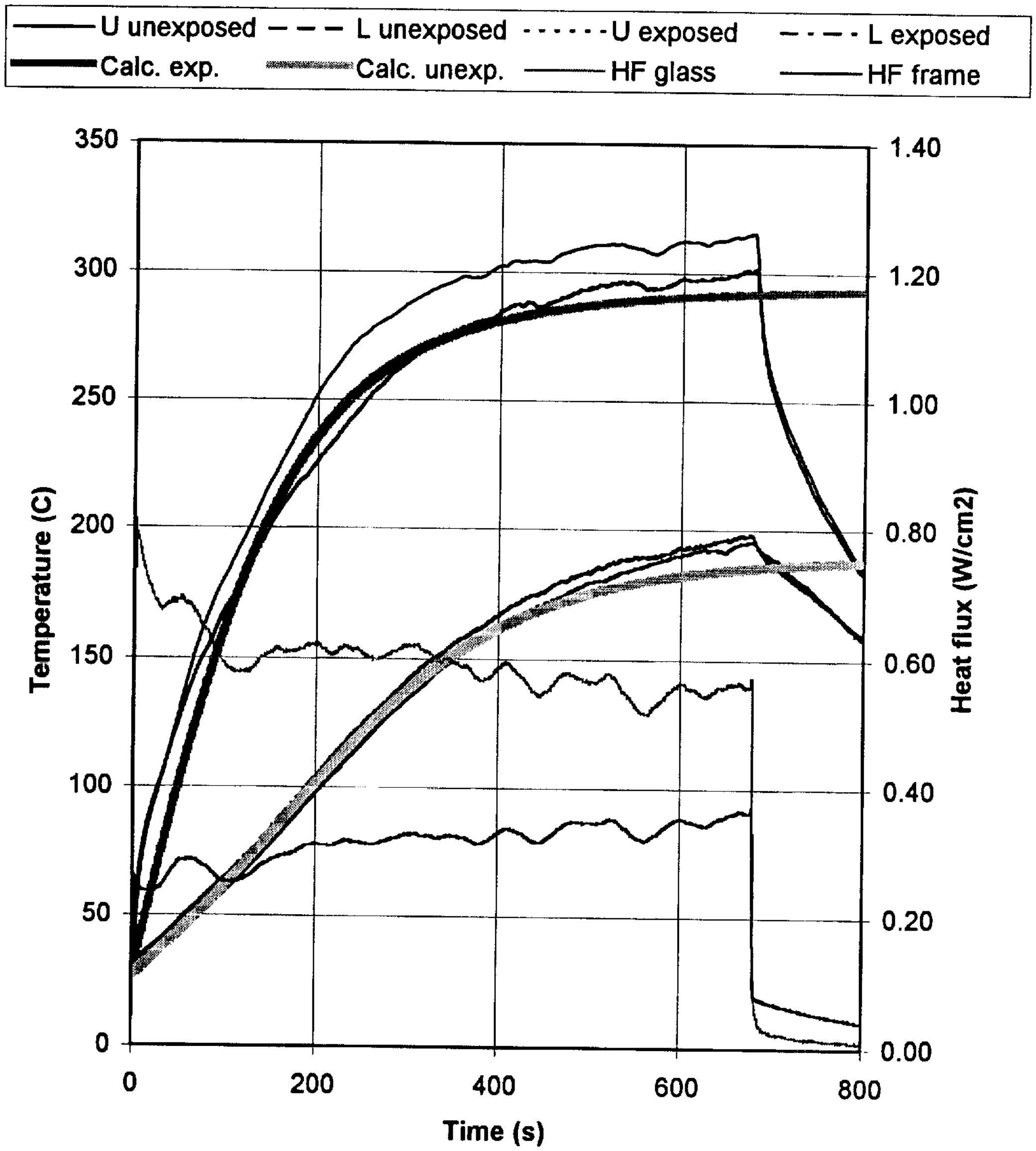

Figure 8. Temperature and heat flux data for large-scale Window Test 4.

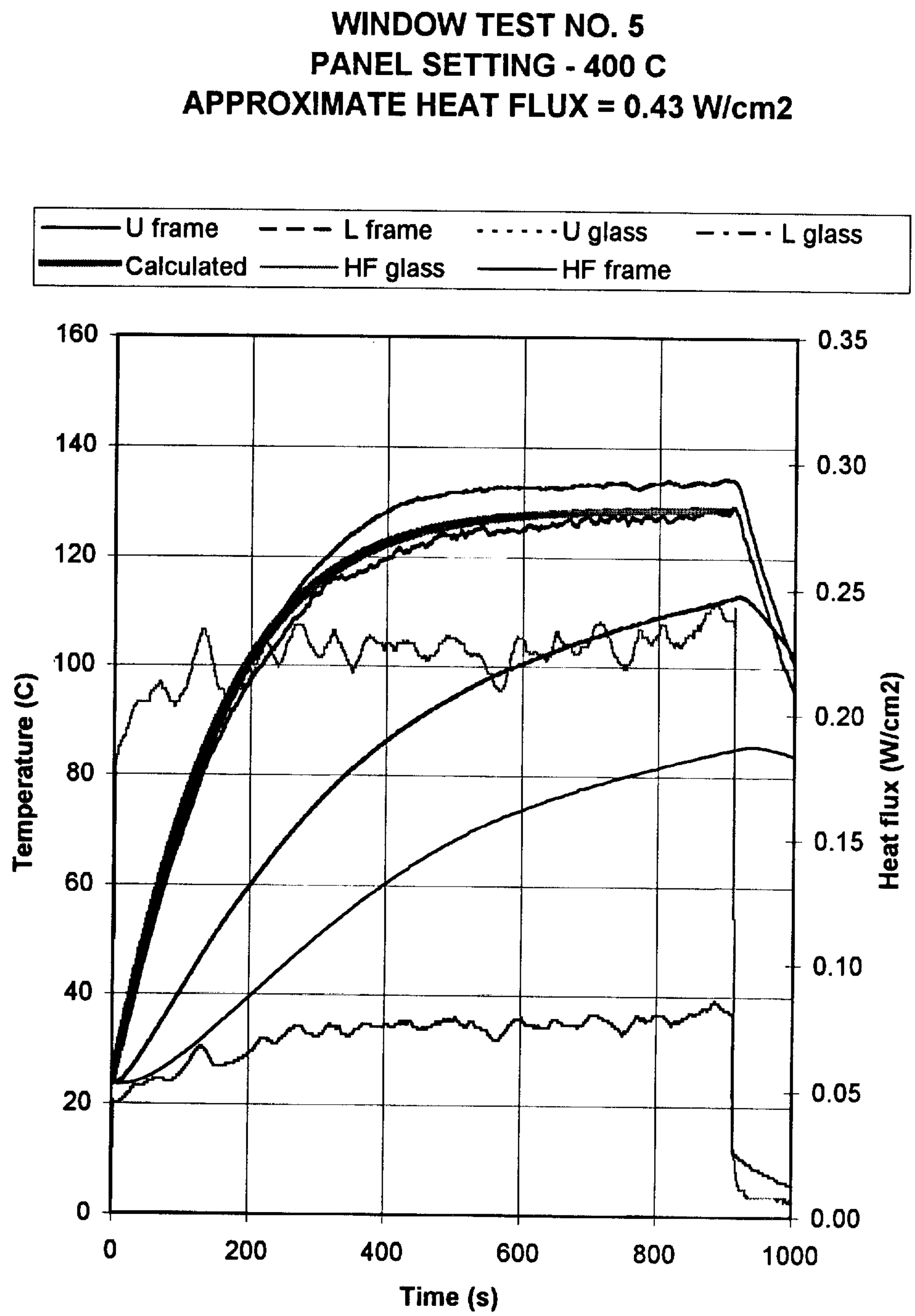

Figure 9. Temperature and heat flux data for large-scale Window Test 5.

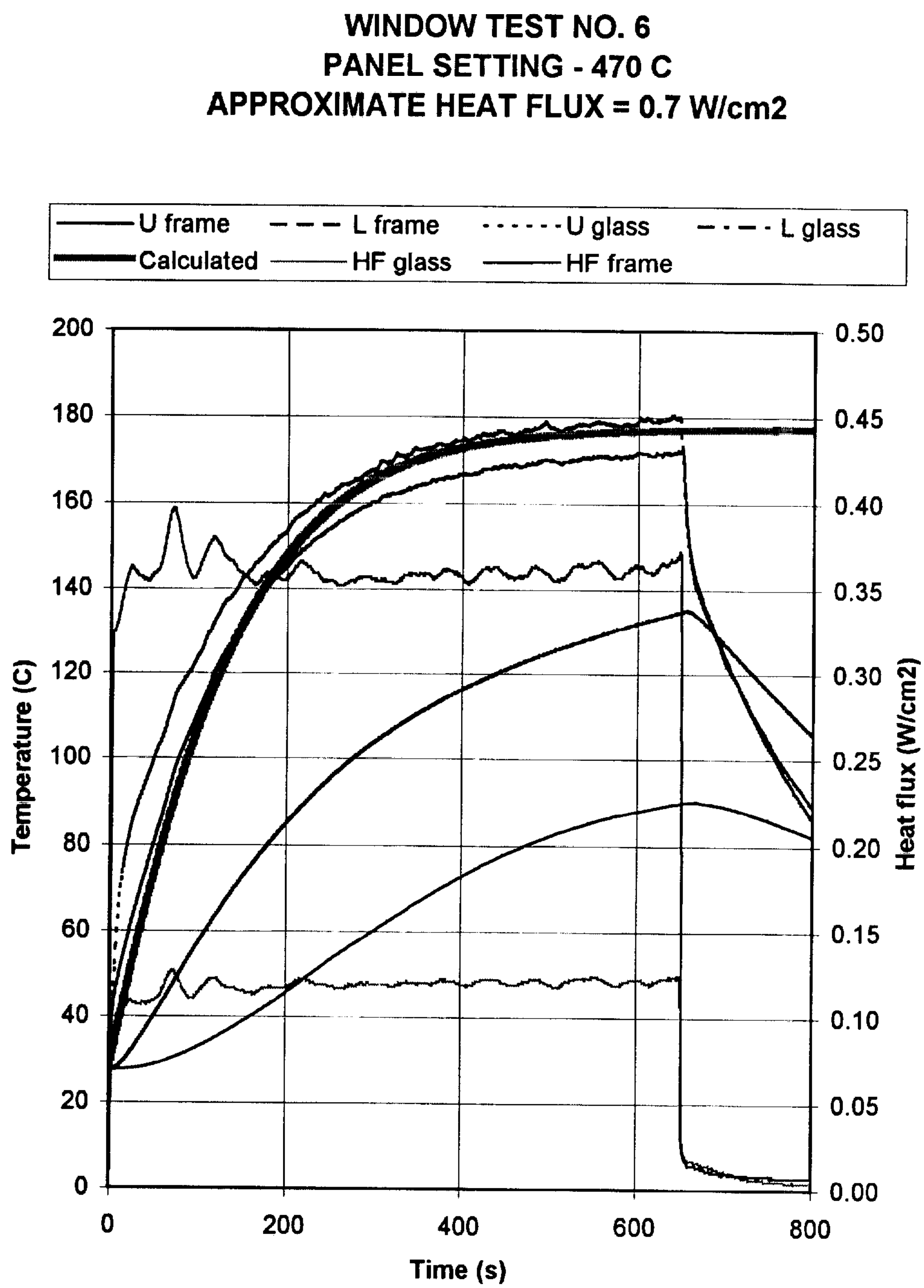

Figure 10. Temperature and heat flux data for large-scale Window Test 6.

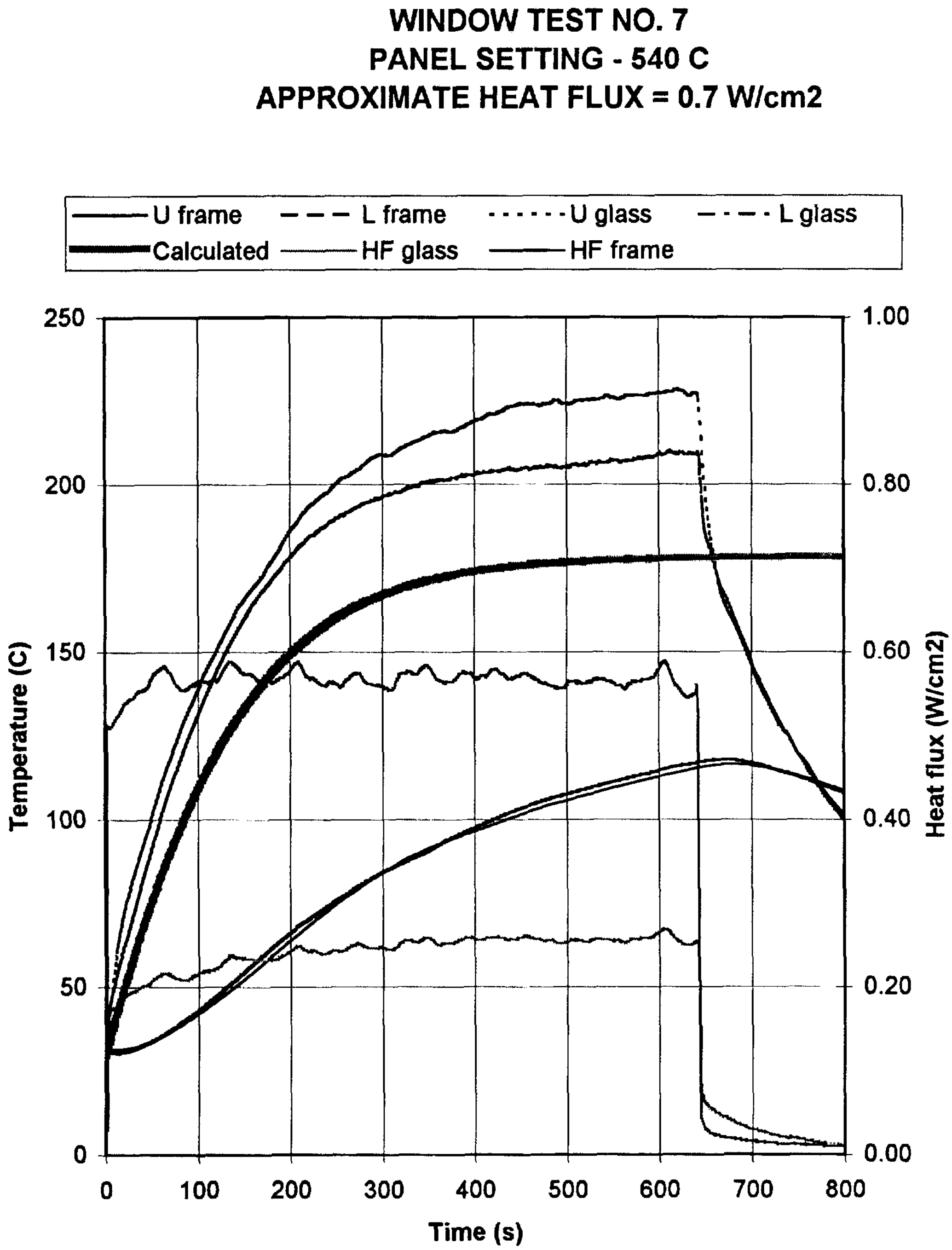

Figure 11. Temperature and heat flux data for large-scale Window Test 7.

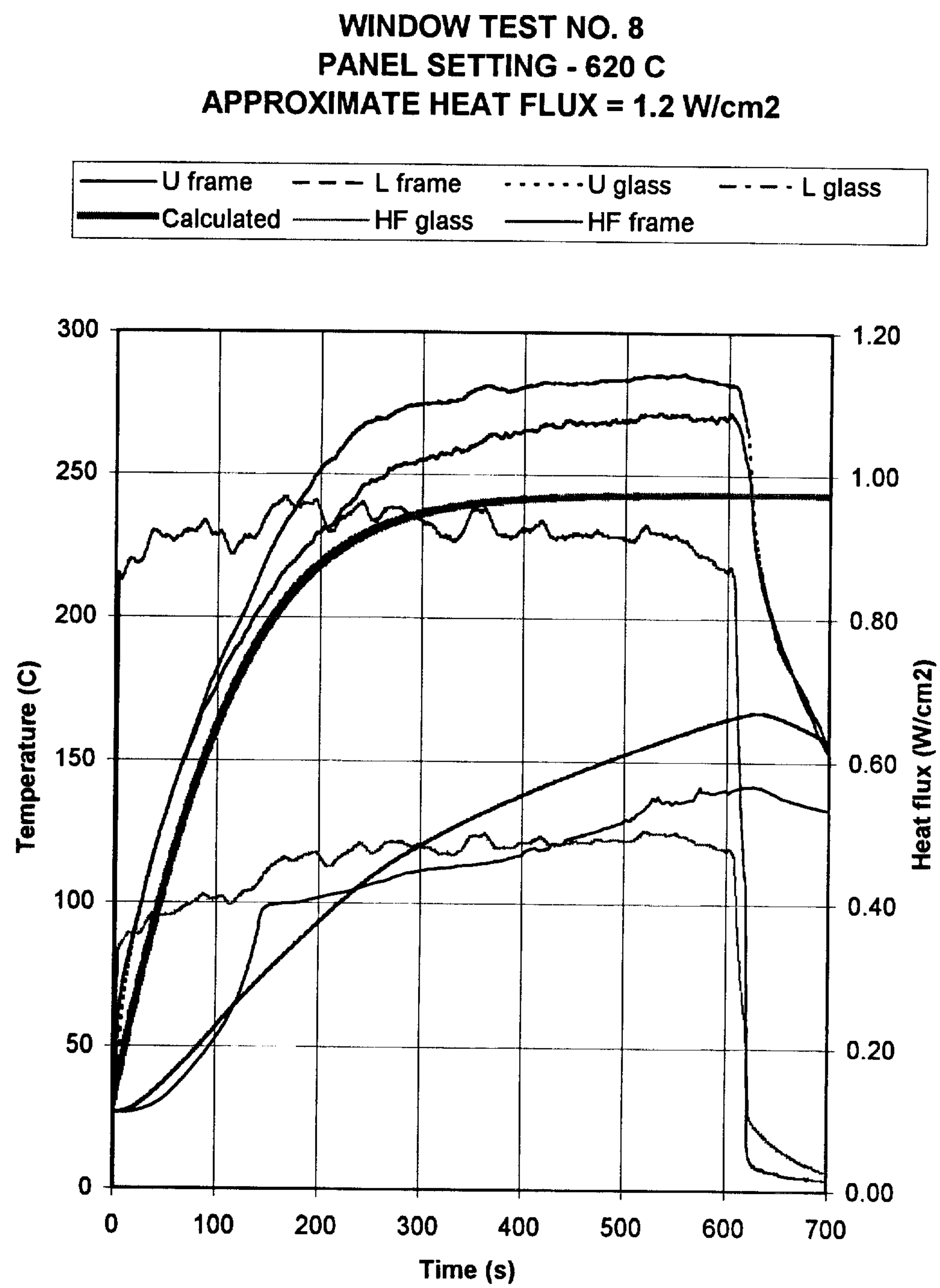

Figure 12. Temperature and heat flux data for large-scale Window Test 8.

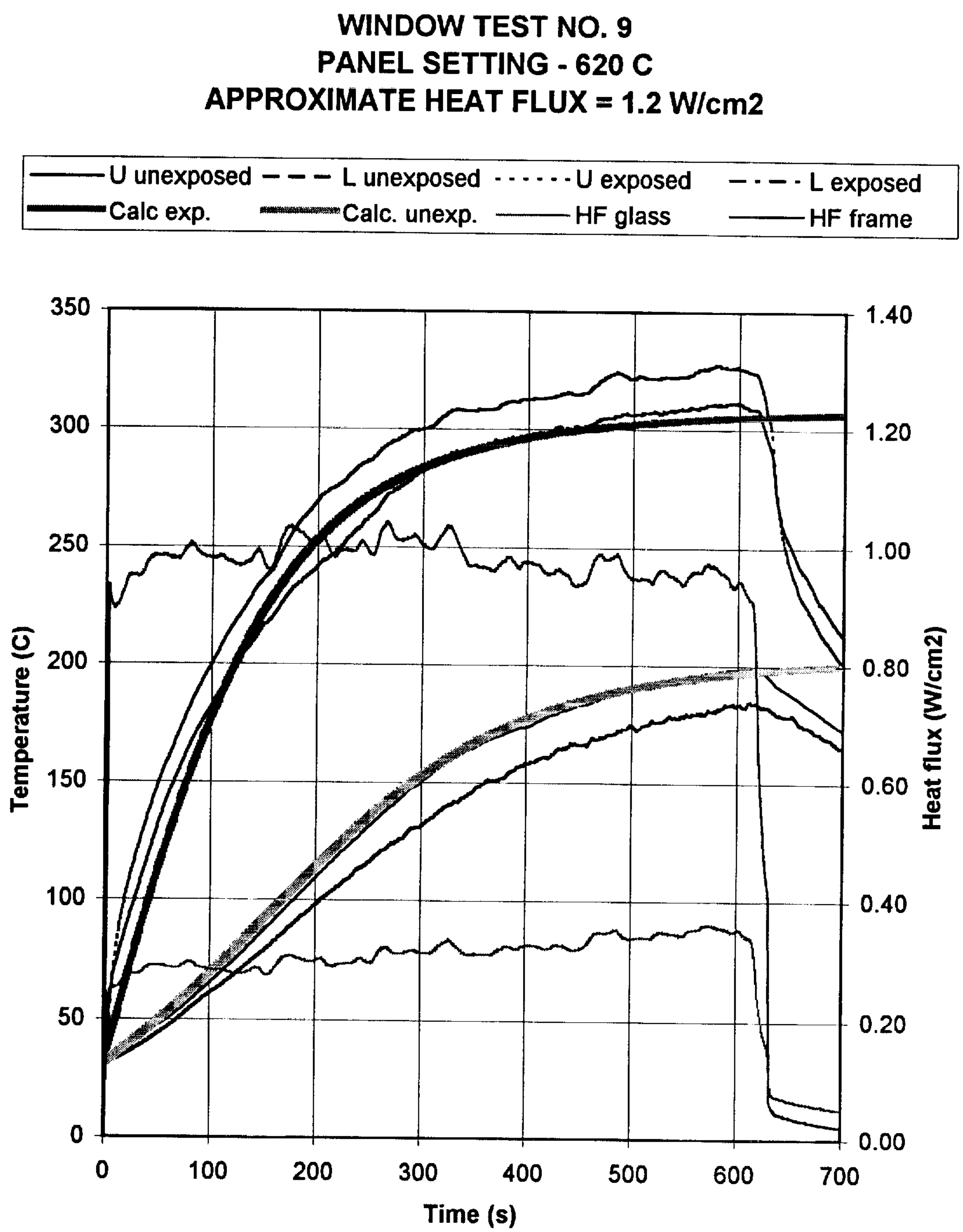

Figure 13. Temperature and heat flux data for large-scale Window Test 9.

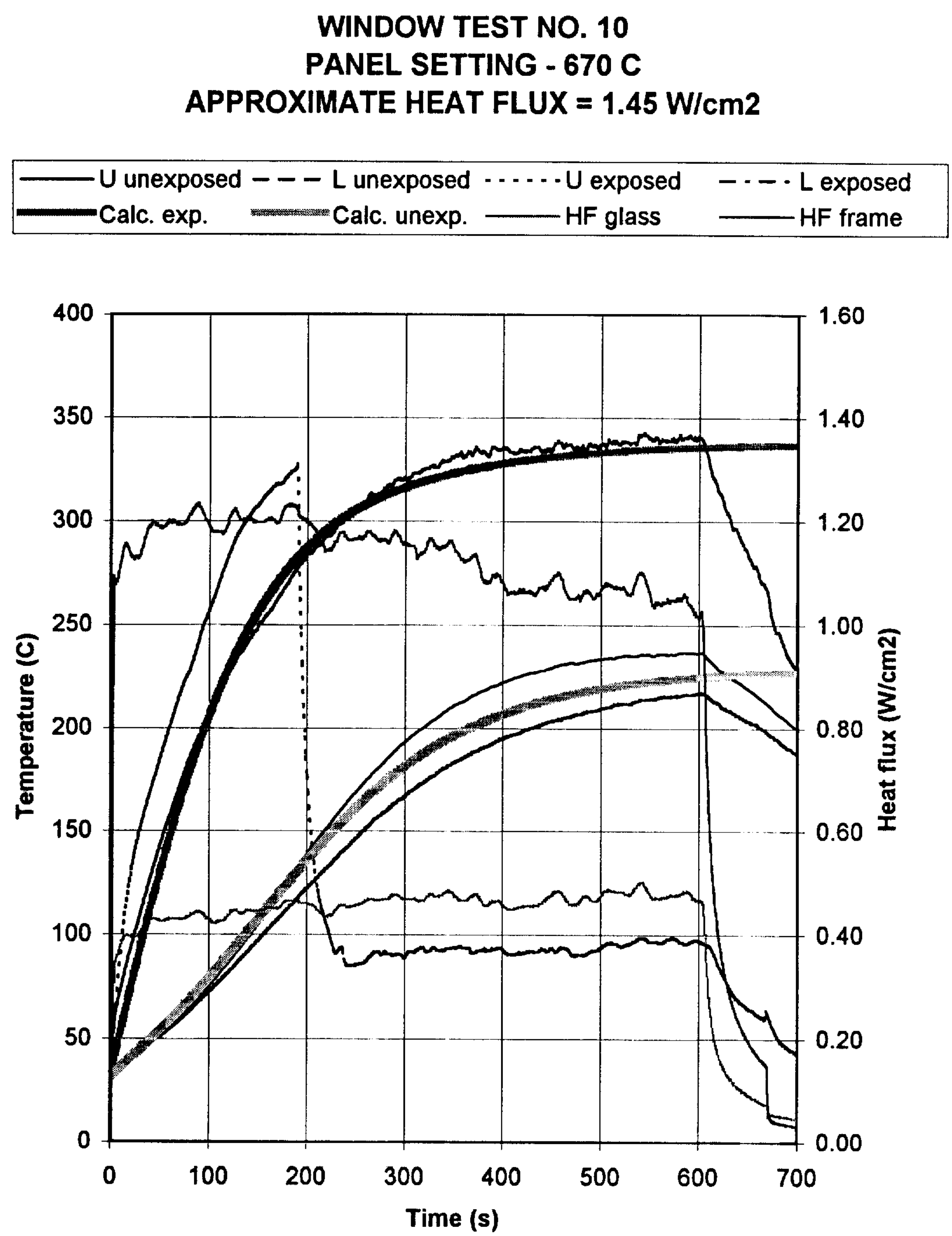

Figure 14. Temperature and heat flux data for large-scale Window Test 10.

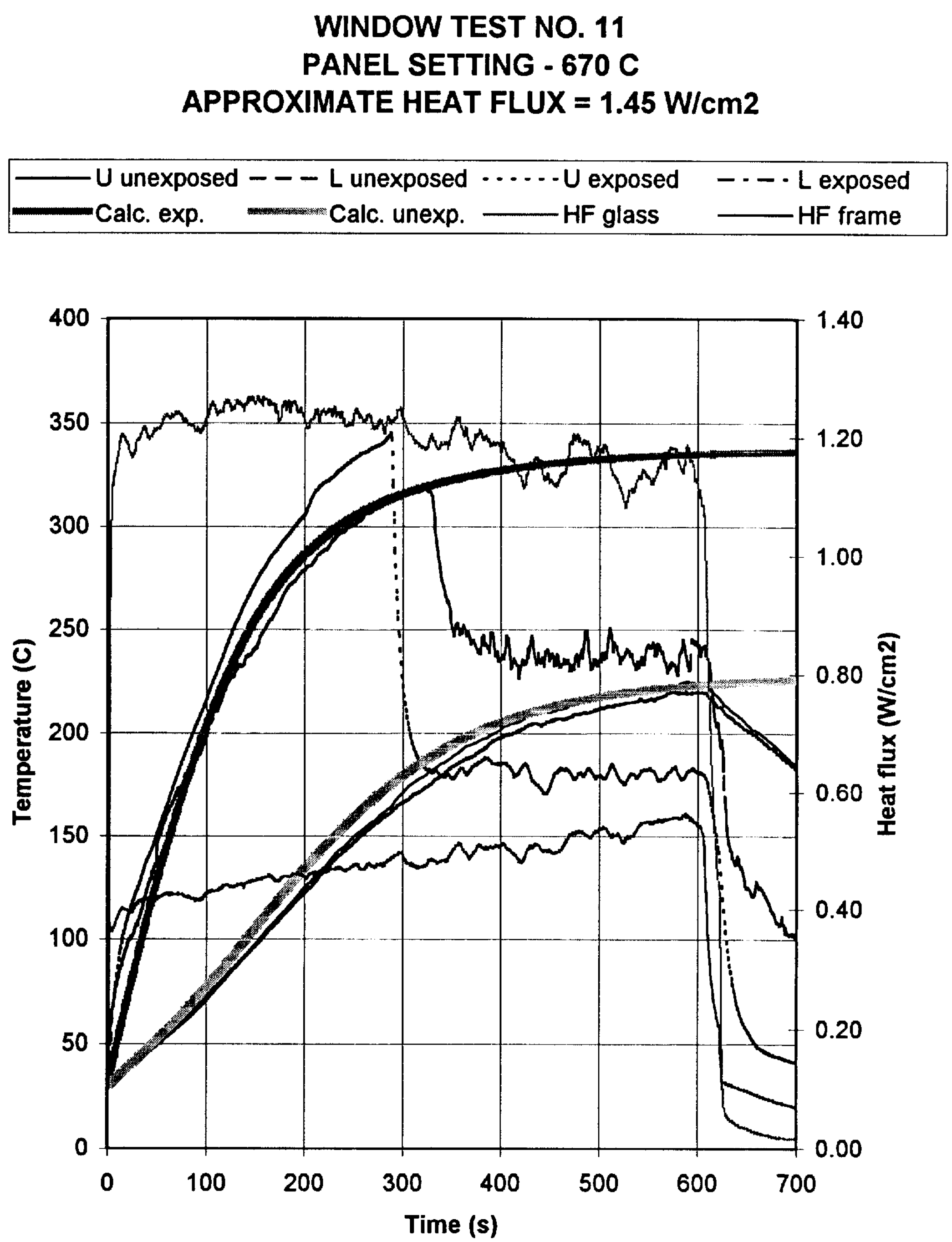

Figure 15. Temperature and heat flux data for large-scale Window Test 11.

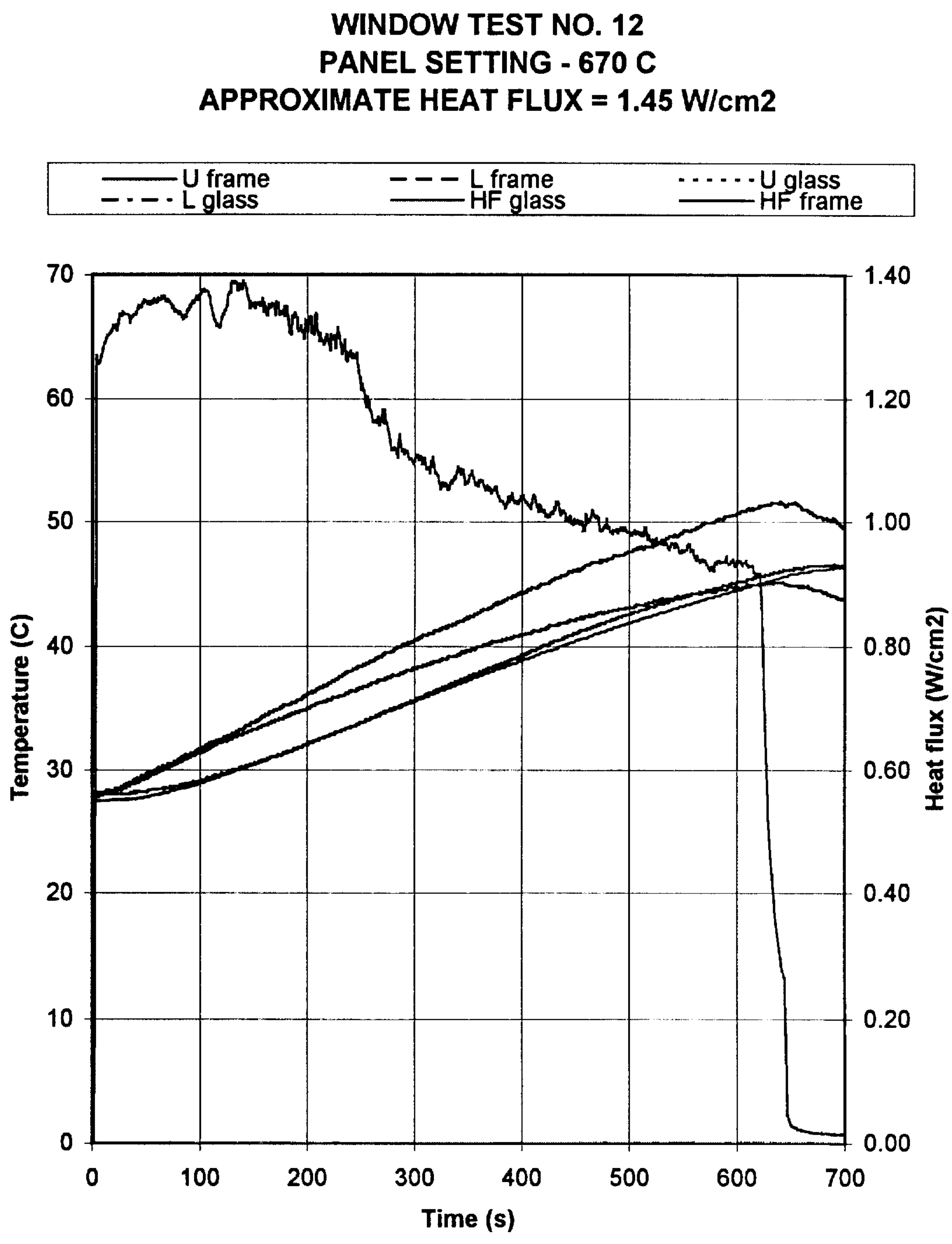

Figure 16. Temperature and heat flux data for large-scale Window Test 12.

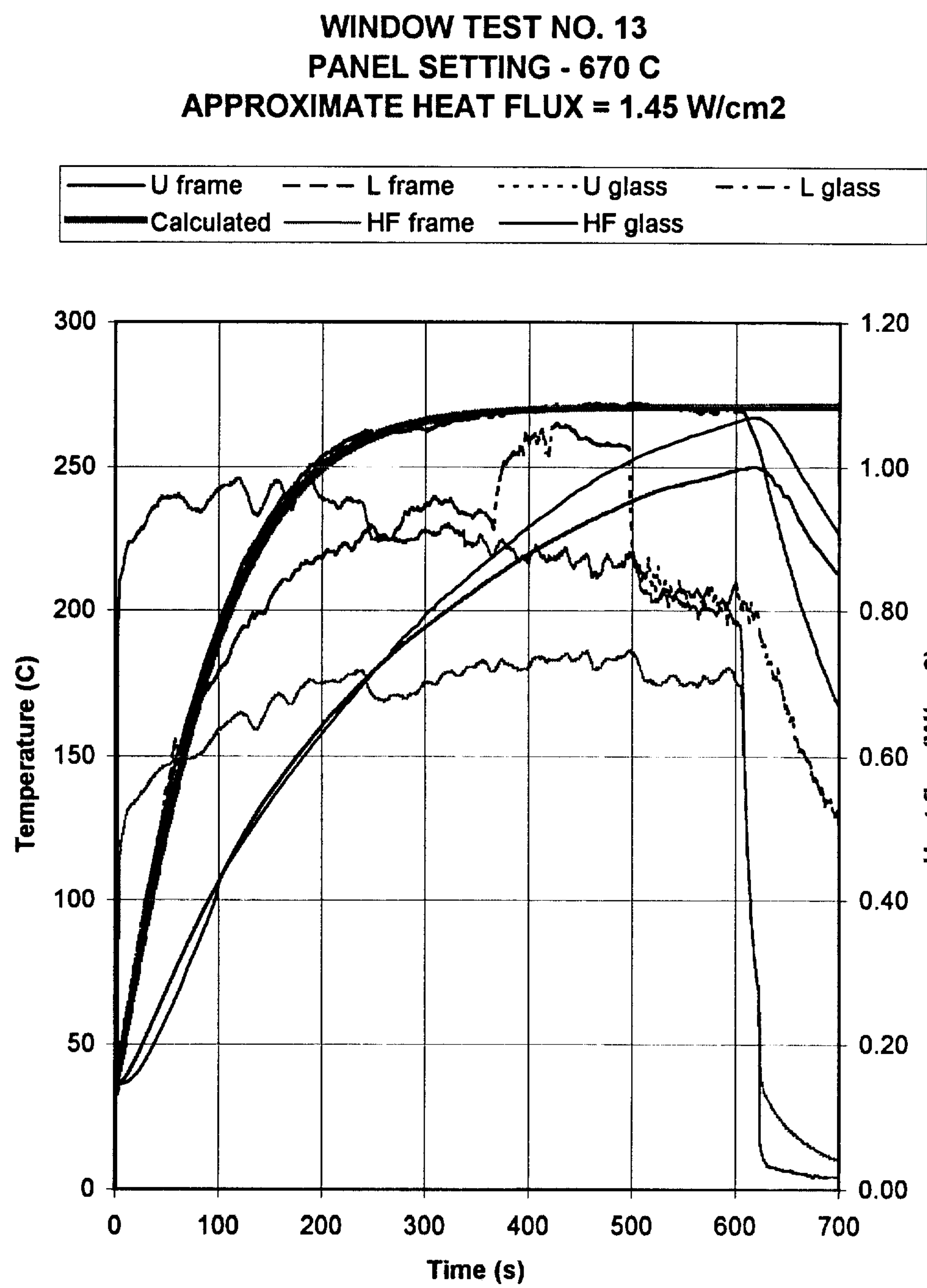

Figure 17. Temperature and heat flux data for large-scale Window Test 13.

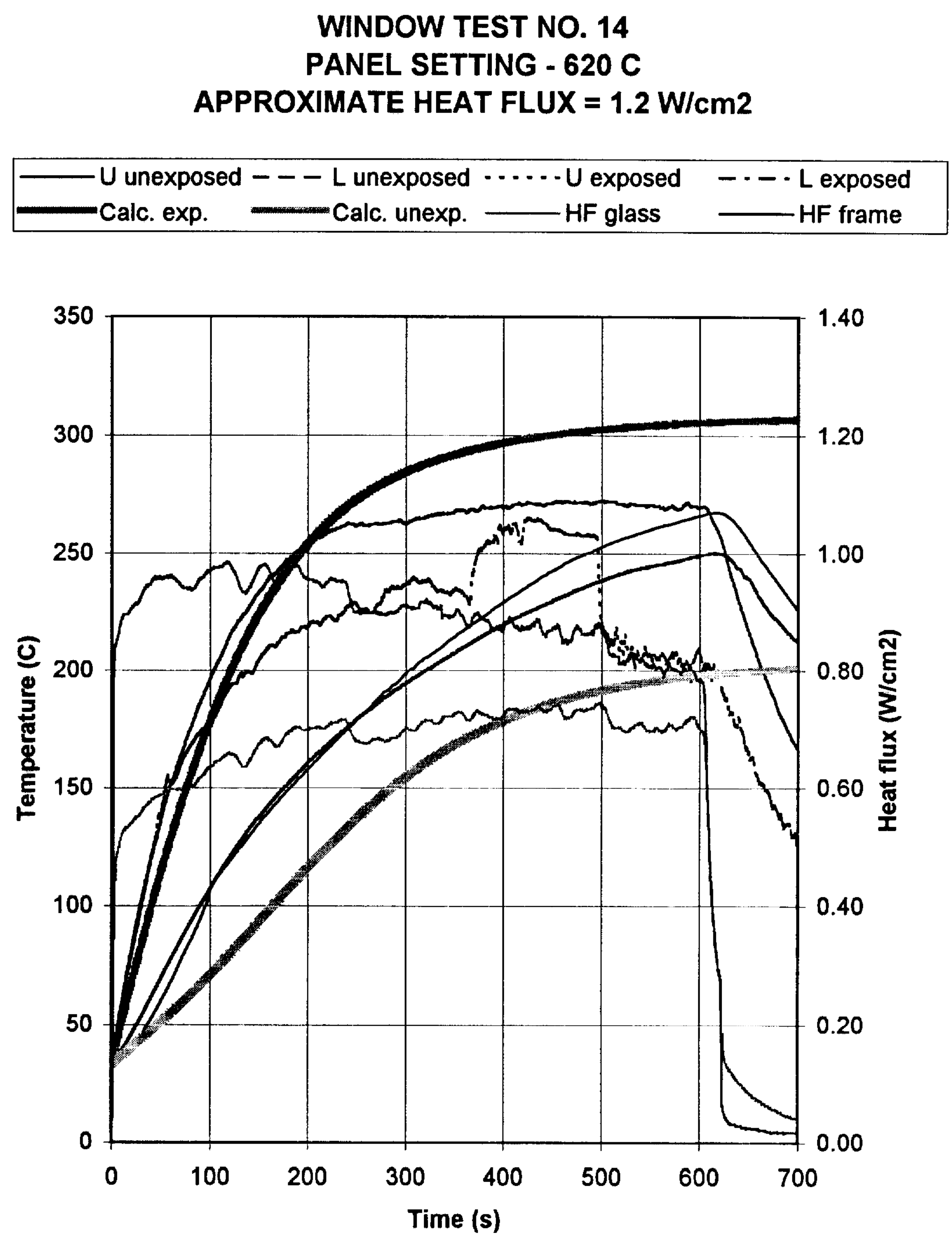

Figure 18. Temperature and heat flux data for large-scale Window Test 14.

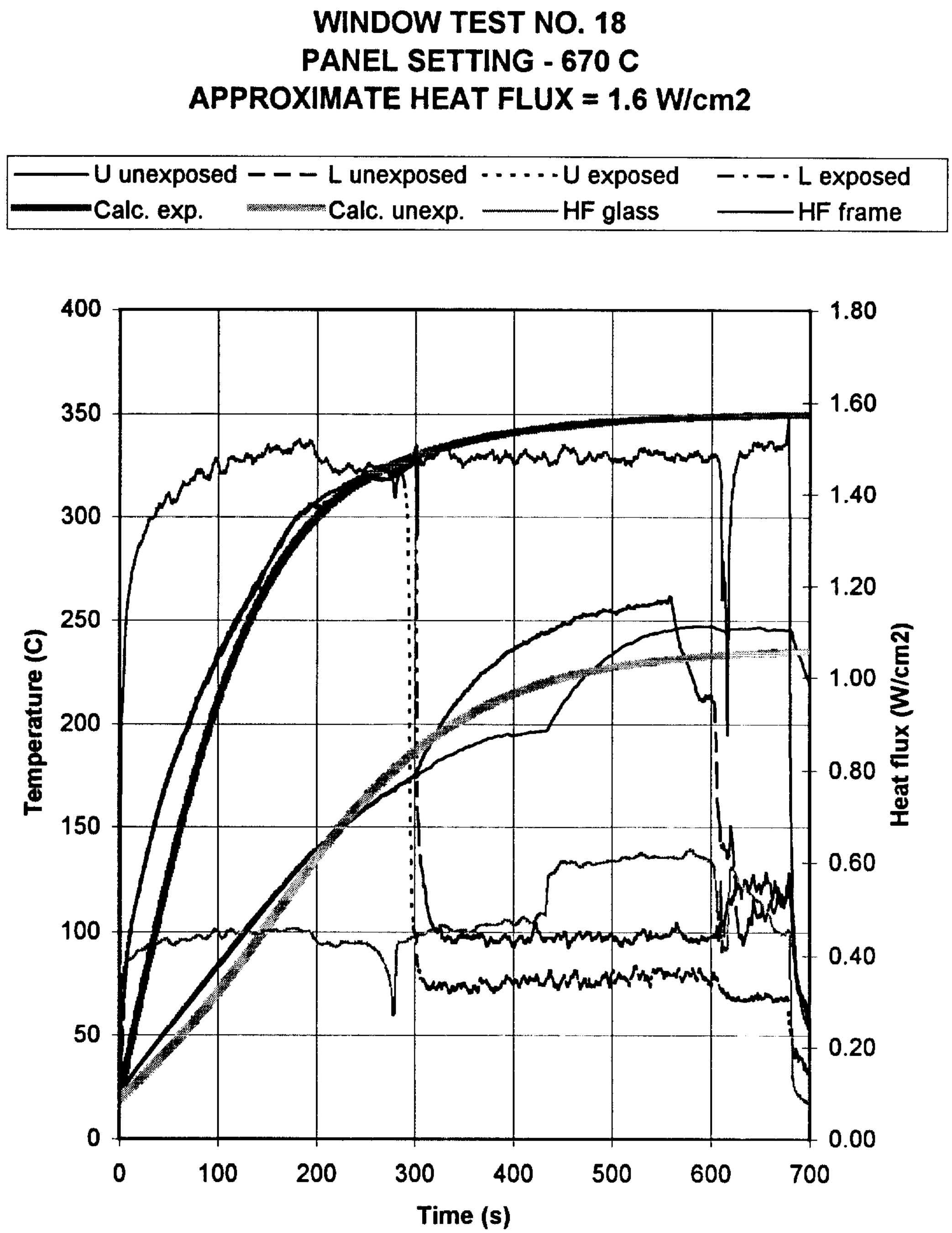

Figure 19. Temperature and heat flux data for large-scale Window Test 18.

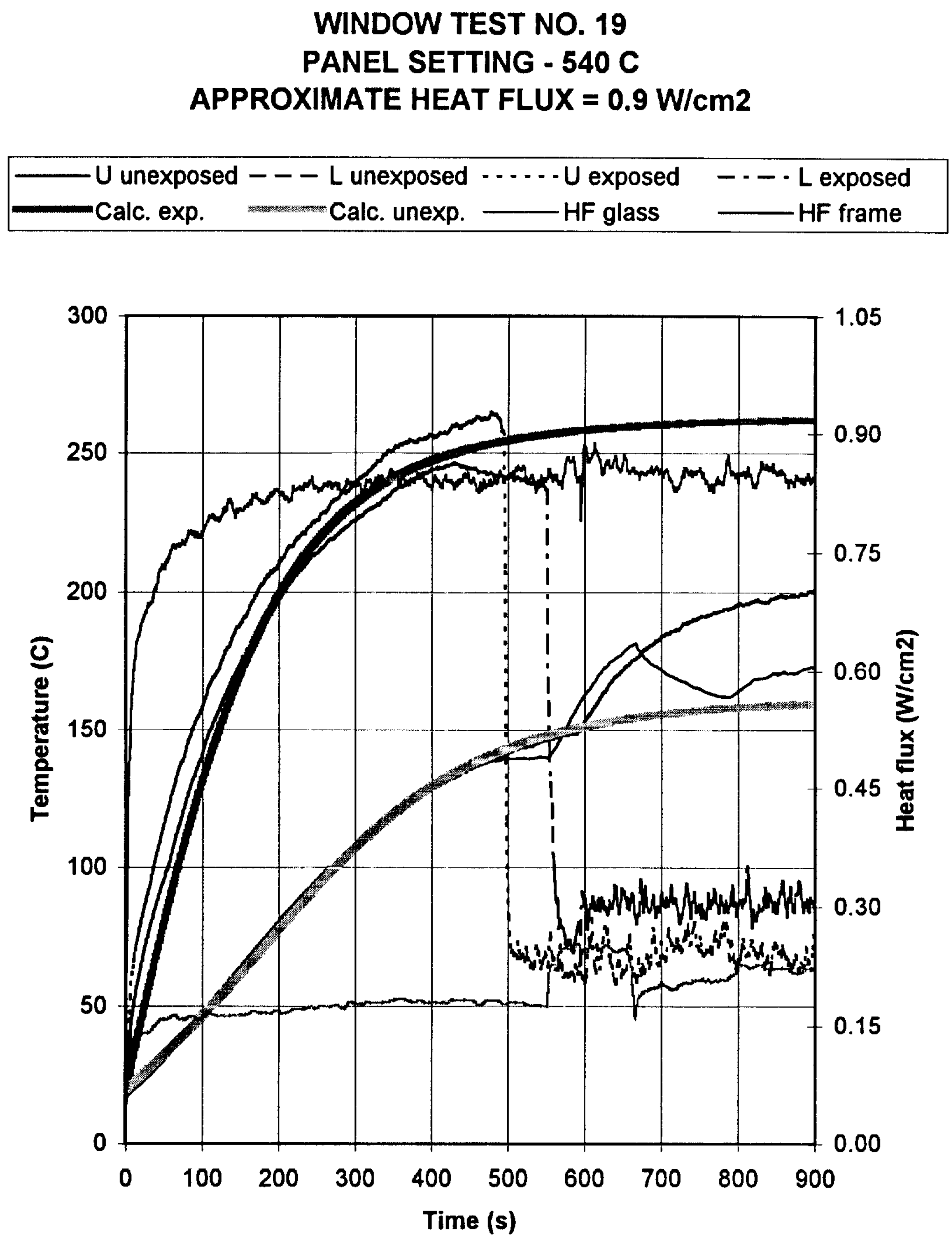

Figure 20. Temperature and heat flux data for large-scale Window Test 19.

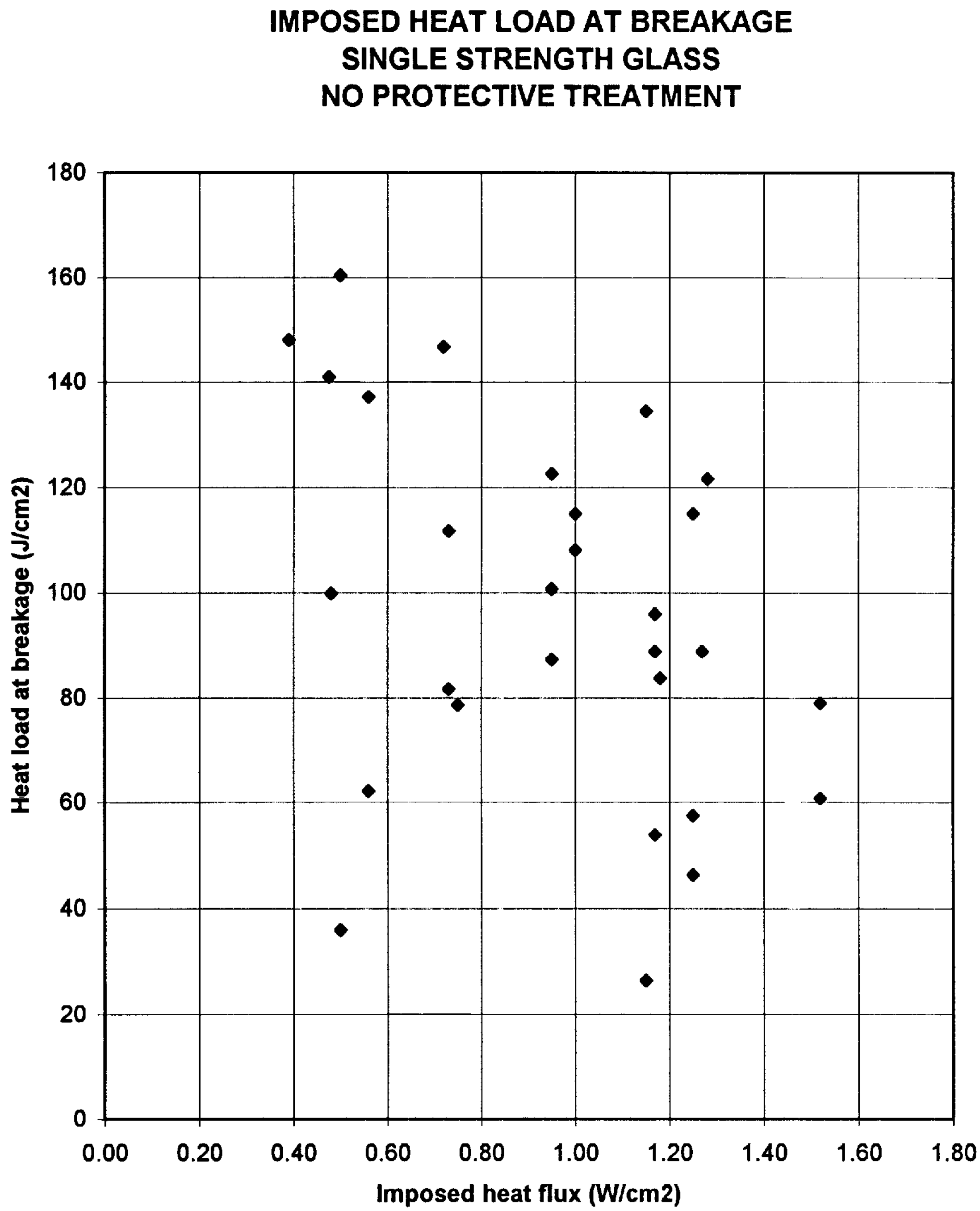

Figure 21. Imposed heat load at fracture data for small-scale experiments.

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Exterior fires can penetrate building envelopes via a number of pathways to become interior fires. One pathway is through windows and other glazed openings that have been broken by fire-induced stresses. A number of small- and large-scale experiments have been conducted to evaluate the performance of various window assemblies, glazing materials and potential protective treatments under the influence of imposed radiant heat fluxes ranging from 0.2 to 1.8 W/cm^2. Window assemblies include single- and double-pane windows with wood, vinyl and vinyl-clad wood frames. Glazing materials include ordinary single- and double-strength plate glass, tempered glass and a heat-resistant ceramic glass. Potential protective treatments include insect screens, vinyl film sun shades and aluminum foil. The application of aluminum foil over the exterior side of a window was found to be an effective treatment to prevent window breakage induced by an exterior fire. This simple treatment could be implemented by homeowners or other occupants of existing buildings in advance of an approaching exterior fire. Tempered glass and heat-resistant ceramic glass did not break under the influence of the imposed heat fluxes; mounted in a suitable fire resistant frame, they could be candidates for use in new windows where exposure to an exterior fire is expected. Vinyl-frame windows did not perform well under the exposure of imposed heat fluxes. The vinyl frames and sashes of these windows lost strength, distorted and sagged, permitting openings to develop. Consequently, vinyl-frame windows would not be suitable for use with fire resistant glazing materials.

KEY WORDS (MAXIMUM OF 9; 28 CHARACTERS AND SPACES EACH; SEPARATE WITH SEMICOLONS; ALPHABETIC ORDER; CAPITALIZE ONLY PROPER NAMES)

building fires; ceramics; fire resistant materials; heat flux; glazing materials; glass; large scale fire tests; wildland urban interface

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